Research Article

Kinematic and electromyography analysis of paraplegic gait with the assistance of mechanical orthosis and walker

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Objective: To investigate the kinematics, functional sub-tasks, and excitation levels of the trunk and upper extremity muscles of paraplegic subjects during walker-assisted locomotion.
Design: Retrospective cross-sectional study.
Setting: Gait analysis laboratory.
Participants: Eight individuals with spinal cord injury at T12, lower extremity motor score less than 4, and capable of walking independently with the assistance of ankle-foot orthosis and walker.
Main Outcome Measures: Kinematics of pelvis, trunk, shoulder and elbow; trajectory of center of mass; and electromyography (EMG) activity of trunk and upper extremity muscles during gait.
Results: Four subtasks were characterized for each locomotion step, based on the kinetics and kinematics data: (1) balance adjustment, (2) walker propulsion, (3) leg raising, and (4) leg swing. The latter two involved large lateral maneuvres by the trunk and pelvis and appeared to be the most skill- and muscle activity-demanding subtasks. The main muscles contributing into these subtasks were the ipsilateral paraspinal and abdominal muscles, as well as the contralateral scapulothoracic and shoulder girdle muscles, with EMG intensities significantly higher than their minimum mean intensities ($P < 0.05$) and those of the contralateral side ($P < 0.05$).
Conclusions: Our results provide more insight into the functional sub-tasks and muscular demands of walker-assisted paraplegic gait that can help to design appropriate muscle strengthening programs, as well as developing more effective gait orthoses.

Keywords: Spinal cord injury, Gait analysis, Functional subtasks, Trunk, Upper extremity

Introduction

The majority of SCI individuals use manual wheelchairs as their primary means of mobility[1] which can deteriorate their mental and physiological health due to prolonged sitting.[2] Standing and walking, even with a crutch or walker, have a significant impact on the independency, cardiorespiratory performance and quality of life of SCI persons.[3–4]

Despite the great advancements in the robotic orthotic technology,[5–7] passive mechanical orthoses are still the most popular assistive devices used by SCI individuals.[1,8] The paraplegic locomotion with such passive orthoses, however, involves a different gait strategy from the normal, in which the trunk and upper extremity muscles (TUEM) play an important role. With the legs paralyzed, the TUEM not only should contribute into the body weight support and balance preservation, by grasping the walker, but they would be also responsible for realizing the required maneuvres at the lower extremities, e.g. leg propulsion.

In spite of the relatively extensive studies concerning the excitation patterns of the TUEM in daily activities of SCI individuals, e.g. video gaming,[9] wheelchair propulsion,[10–13] depression transfer,[14,15] and balance preservation,[16] there is no study in the literature investigating the contribution of the TUEM

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into the paraplegic gait, except for some recently published case reports on single SCI individuals.[17,18] The objective of this study, hence, is to provide a detailed description of the role and significance of the TUEM in the walker-assisted paraplegic locomotion, in association with the functional subtasks of the gait. For eight SCI individuals, the functional subtasks of the gait cycle are characterized using the kinetics and kinematics observations, and the electromyography (EMG) activity of the TUEM during each subtask is investigated. It was hypothesized that at each subtask of the paraplegic gait, some specific TUEM have significantly higher excitation levels than their minimum mean intensities, indicating their major contributions into the kinematic and dynamic maneuvres of that subtask. The results can help to understand the role and significance of each of the TUEM in the critical subtasks of the paraplegic gait, i.e. leg raising and leg swing, and planning more efficient muscle strengthening programs for SCI individuals. Moreover, they can provide useful suggestions for improving the efficiency of the paraplegic gait pattern and designing more effective walking orthoses.

Method

Eight male subjects with SCI level at T12 were recruited for this study. The detailed clinical demographics of the subjects, including the ISNCSCI (International Standard for Neurological Classification of Spinal Cord Injury) motor scores[19] and the ASIA (American Spinal Injury Association) grade are indicated in Table 1. Participants enrolled in a similar rehabilitation program including physical and occupational therapy, and at least 6 months of training to walk independently with the aid of a bilateral AFO and a walker. Exclusion criteria included: lower extremity motor score greater than 12 (25% of the scale), any experience of shoulder pain or injury related to the trunk and the upper limbs, and weakness in TUEM lower than 4/5 examined by manual muscle test. Prior to the study, each subject was provided with a copy of the Bill of Rights of Human Subjects and read and signed an informed consent form that had been approved by the university ethics committee.

For each subject, at least ten gait cycles with complete kinematics, force and EMG data were collected. During the tests, the subject was instructed to walk at his comfortable speed on a level surface along a 10-meter walkway. Kinematics data was recorded using an eight-camera motion analysis system (Vicon Motion Systems, Oxford Metrics Inc., UK) at 120 frame/second with the markers attached to the anatomical landmarks based on a standard marker placement protocol.[20] The ground reaction forces were measured using two force plates (Kistler Instrument AG, Switzerland) at 1200 Hz. The joints motions were found using the Plug-in Gait Model,[20,21] and the trajectory of the center of mass (CoM) using the kinematic centroid method (Nexus, Vicon Motion Systems, Oxford, UK).

The surface EMG data was recorded bilaterally from the TUEM using a radio telemetry device (Myon Ltd, Switzerland) with a signal-to-noise ratio of 1.2 uV and a fixed gain of 1000. The skin was dry-shaved, abraded and cleaned by alcohol pad. Pairs of Ag/AgCl disc electrodes with a solid gel diameter of 10 mm and an inter-

Table 1 Subject demographics.

Subject	Sex	Months post SCI	Age (years)	Weight (kg)	Height (cm)	SCI level	Lower extremity motor score Right/Left (max 25/25)	Upper extremity motor score Right/Left (max 25/25)	ASIA grade	Dominant side	Cause
1	M	19	30	65	170	T12	2/2	25/25	B	Right	Car Accident
2	M	15	29	56	169	T12	2/1	25/25	B	Right	Car Accident
3	M	32	20	74	179	T12	2/2	25/25	B	Right	Car Accident
4	M	14	35	71	182	T12	1/1	25/25	B	Right	Car Accident
5	M	18	25	60	191	T12	3/3	25/25	C	Right	Car Accident
6	M	16	28	86	183	T12	3/3	25/25	C	Right	Car Accident
7	M	12	29	55	181	T12	1/2	25/25	B	Right	Car Accident
8	M	18	49	73	174	T12	2/2	25/25	C	Right	Fall
Range		12–32	20–49	55–86	169–191	T12	1-3/1-3	25/25	C-B	Right	

electrode distance of 20 mm were used in bipolar configuration over the muscle belly and parallel to muscle fibers. Electrode placements were based on the guidelines suggested by McGill *et al.*[22] and others.[23–26] The muscles under study included the Triceps Long Head (TC), Posterior Deltoid (PD), sternal portion of Pectoralis Major (PM), Latissimus Dorsi (LD), Lower Trapezius (LT), Longissimus (LG), Iliocostalis (IC), Quadratus Lumborum (QL), External Oblique (EO), Internal Oblique (IO) and Rectus Abdominis (RA). These muscles were selected based on the results of our previous study[27] which showed they have considerable EMG activities during paraplegic gait.

For each muscle group, the EMG associated with the maximum voluntary contraction (MVC) tests were also recorded for 10 s, based on the guidelines described in the literature. In the MVC tests of trunk muscles, the subjects attempted isolated thorax flexion/extension, left/right lateral bending, or left/right rotation, against a manually applied resistance, while the pelvis was restrained.[24] Similarly, in the MVC tests of the shoulder girdle muscles, the subjects attempted performing a number of tasks in different positions, described in detail by Kendal *et al.*,[28] Boettcher *et al.*,[29] and Ekstrom *et al.*,[30] against manual resistance.

The EMG signals were sampled at 1200 Hz and analog-to-digitally converted with 14-bit resolution (National Instruments, US). The digital data was then high-pass filtered using fifth order butterworth at 30 Hz,[31] demeaned, full wave rectified, low-pass filtered using a fourth order butterworth at 5 Hz.[32] To avoid phase lag, all filters were applied recursively. Finally, the EMG data of each TUEM during paraplegic gait was normalized against its highest one-second activity during the relevant MVC test.[33]

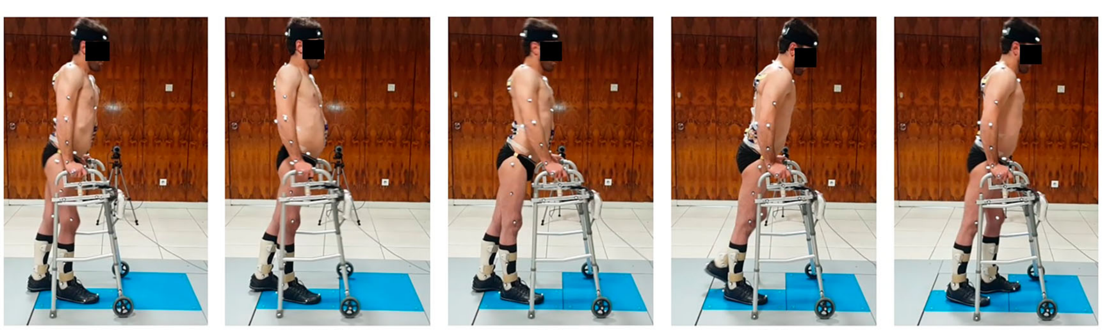
The functional subtasks of the paraplegic gait cycle were distinguished considering the essential biomechanical subtasks involved in human gait, such as body support, forward propulsion and leg swing, and their timings were characterized using the kinematics and force plate data. The mean duration of each subtask was found by averaging the time percentage of that subtask from the whole gait cycle duration of each subject. The kinematics and EMG results were then time normalized for the mean duration of each subtask, and their means for all subjects were determined.

In order to identify the significance of each TUEM in the subtasks of the paraplegic gait cycle, first the means of its EMG intensities at different subtasks were calculated and the normal distribution of the data of each subtask was screened using Shapiro Wilks test. Among the mean intensities, the smallest one, which could be associated with any of the eight subtasks, was considered as the minimum mean intensity (MMI) of the muscle throughout the gait cycle. Then, the mean intensities of the muscle at different subtasks were compared with its MMI using paired t-test (significance level set at 0.05). A muscle was considered as the main contributor into a subtask if it had a significantly higher mean intensity compared to its MMI. Also, in order to determine if a muscle is activated unilaterally or bilaterally during a subtask, its mean EMG intensity was compared with that of the other side using the same method.

Finally, to check the gait symmetry, Pearson correlation coefficients were computed for the kinematics and EMG data of a right and a left side step. All data processing was performed using custom-made codes in Matlab (The Mathworks, Inc., Natick, MA, USA).

Results

The gait of the paraplegic subjects was highly symmetrical for both the kinematics (average Pearson correlation coefficient 0.96 ± 0.02) and the muscle activations (average Pearson correlation coefficient 0.93 ± 0.51). Four major subtasks were distinguished for each step of the paraplegic locomotion, based on the kinematics and kinetics results: (1) balance adjustment, (2) walker propulsion (3) leg raising, and (4) leg swing (Fig. 1).



(a) (b) (c) (d) (e)

Figure 1 The sequence of the subtasks of a paraplegic gait left side step. (a–b) balance adjustment, (b–c) walker propulsion, (c–d) leg raising, and (d–e) leg swing.

The normalized durations of these subtasks were 6 ± 0.6%, 9.0 ± 1.2%, 16 ± 2.1%, and 19 ± 2.8% of the gait cycle, respectively. Figure 2 illustrates the kinematics of the pelvis, trunk, shoulder and elbow, as well as the CoM trajectory, during these subtasks for a gait step. Also, Figure 3 indicates the share of the body weight support between the walker and the lower extremities during the subtasks. The normalized mean intensities of the EMG signals of the TUEM during the subtasks are illustrated in Figure 4.

In the balance adjustment subtask (Fig. 1a,b), beginning with a right foot contact, the subjects attempted obtaining a temporary upright standing balance on the legs, less dependent upon the walker, in order to enable pushing the walker forward in the next subtask. The main kinematic maneuvres of this subtask were pelvis right rotation and left side elevation (Fig. 2), which shifted the CoM towards the right (near the just landed leg) and forward. The body weight was supported mainly (89.0 ± 9.2%) by the lower extremities during this subtask (Fig. 3). The main contributing TUEM into this subtask were the contralateral PD, LD, LT, LG, IC and QL, with EMG intensities significantly higher than their MMIs ($P < 0.05$) (Fig. 4). The intensities of these muscles, however, were significantly higher than the ipsilateral ones only for the LD and IC ($P < 0.05$), where for the latter the intensity of the ipsilateral muscle was also significantly higher than its MMI ($P < 0.05$) (Fig. 4).

The objective of walker propulsion subtask (Fig. 1b, c), was to push the walker forward with the hands. The main kinematic maneuvres of this subtask were shoulder extension, trunk flexion, and pelvis anterior tilt (Fig. 2). As shown in Fig. 3, a higher portion of the body weight (36.1 ± 6.3%) was transferred to the walker during this subtask. The main contributing TUEM into this subtask were the bilateral TC, LD, LG, and IC, the ipsilateral IO, and the contralateral PD and RA, with intensity levels significantly higher than their MMIs ($P < 0.05$) (Fig. 4).

In the leg raising subtask (Fig. 1c,d), the subjects attempted producing a foot clearance for the swing (left) leg. The main kinematic maneuvres of this subtask were pelvis left rotation and left side elevation, as well as trunk rotation to the left and lateral flexion to the right (Fig. 2). The trunk movements were helped by the ipsilateral shoulder extension, adduction and external rotation, and the contralateral shoulder internal rotation, as well as the ipsilateral elbow extension and the contralateral elbow flexion (Fig. 2). This subtask involved the largest forward shift of the CoM, and the largest body weight support (70.0 ± 5.2%) by the walker (Fig. 3). The main muscles contributing into this subtask were the bilateral TC and PD, the ipsilateral PM, LD, LG, IC, EO, and IO, and the contralateral LT, with EMG intensities significantly higher than their MMIs ($P < 0.05$) (Fig. 4). For all unilaterally activated muscles, the intensity levels were significantly higher than those of the other side ($P < 0.05$), except for the IO.

The objective of the leg swing subtask (Fig. 1d,e), was to move the swing (left) leg forward to accomplish a gait step. The main kinematic maneuvres of this subtask were pelvis posterior tilt and right rotation, as well as trunk right rotation and extension (Fig. 2). Again, the trunk movements were helped by the shoulder bilateral flexion, abduction, and external rotation. The CoM moved laterally to the right and then to the left and shifted slightly forward, and the walker supported 61.0 ± 3.1% of the body weight during this subtask (Fig. 3). The main contributing TUEM into this subtask were the ipsilateral PM, LD, LG, IC, QL, EO, and RA, and the contralateral TC, PD, and LT, with EMG intensities significantly higher than their MMIs ($P < 0.05$) and those of the other side ($P < 0.05$).

The leg swing subtask terminated with a pelvic lateral tilt to the left (Fig. 2) in order to enable a smooth landing on the ground and to be prepared for the weight bearing in the next subtask of the gait cycle, i.e. the balance adjustment for the contralateral leg step.

Discussion

This study provided a detailed description of the kinematics, kinetics and muscle activity characteristics of the walker-assisted paraplegic locomotion. In particular, it distinguished the basic functional subtasks of the gait based on their specific objectives, as suggested in the literature for pathological gait description,[34,35] and utilized the gait kinematics and kinetics to characterize their timings. This approach helped to comprehend the complicated maneuvres of the SCI individuals during walker-assisted locomotion and analyzing the associated muscular demands.

An interesting observation of this study was the fact that the kinematic maneuvres were realized mostly by the reverse actions of the TUEM. In general, a muscle contraction can move the distal segment towards the proximal one or vice versa, depending on their relative stability; the segment with higher stability remains stationary and the other segment moves. In most physiological activities, e.g. the swing phase of normal gait, the trunk is the most stable body part.[36] As a result, the distal segments, i.e. the lower and upper extremities,

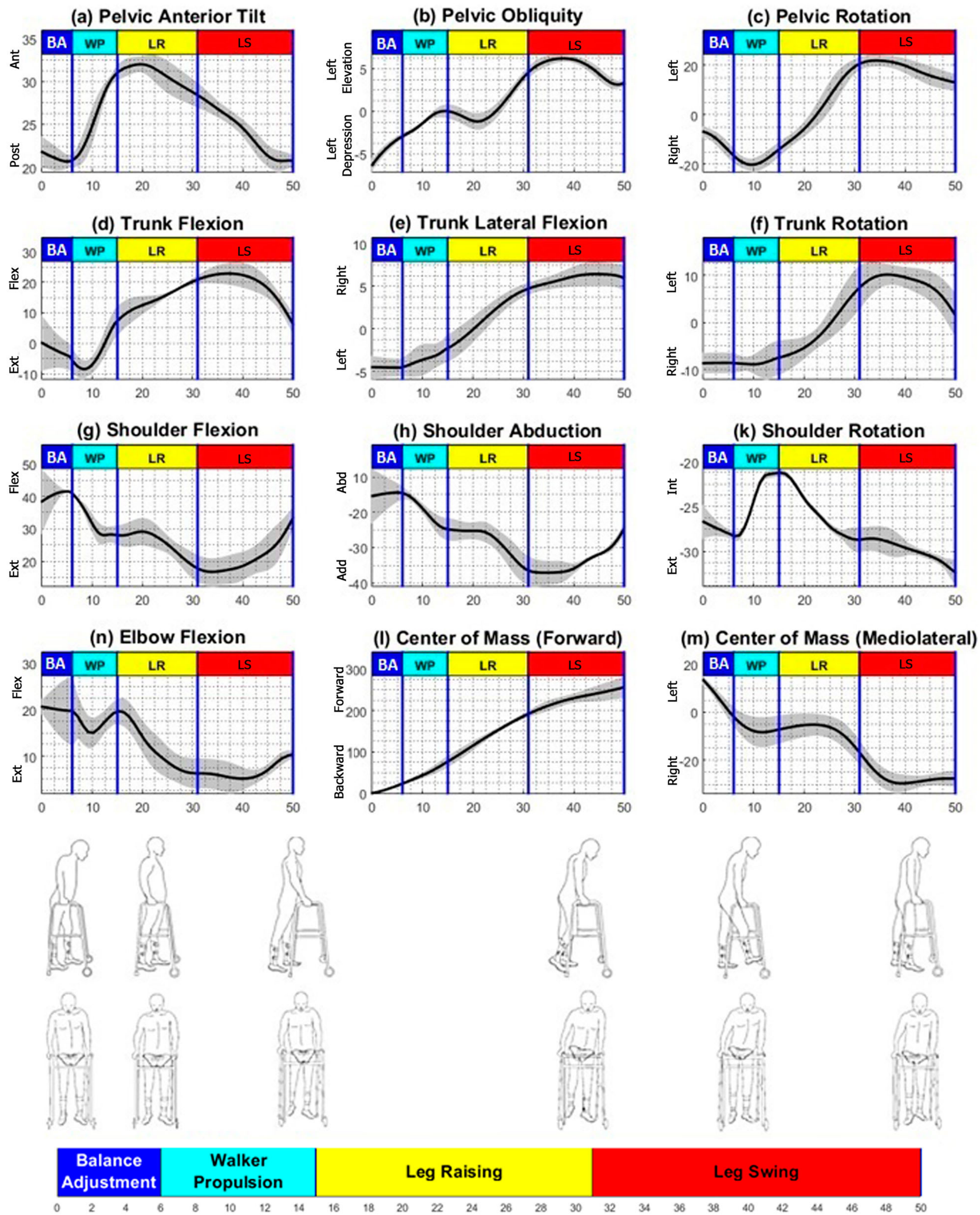


Figure 2 **The kinematics of pelvis, trunk, shoulder and elbow, and the trajectory of the center of mass during the functional subtasks of a left step. The solid lines represent the means of eight subjects, whereas the surrounding lighter shades mark the standard deviations. BA, balance adjustment; WP, walker propulsion; LLR, left leg raising; LLS, left leg swing.**

move via the contraction of the relevant muscles. In the walker-assisted paraplegic gait, however, the whole arm strands fixed to transfer a large portion of the body weight to the walker. Hence, the upper extremities have a higher stability than the trunk, and the TUEM act reversely; their contractions contribute into the

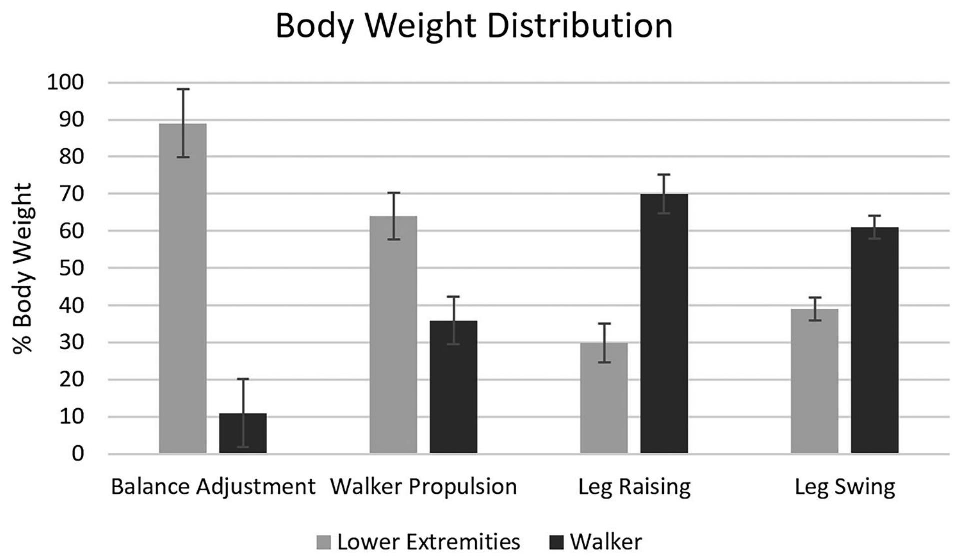


Figure 3 The share of the body weight support between the lower extremities and the walker during the basic subtasks of the paraplegic gait.

motions of the trunk and then the pelvis and the lower extremities.[37]

The results of our study (Figs 2 and 4) indicate that the leg raising and leg swing are the most skill- and muscle activity-demanding functional sub-tasks of the paraplegic gait. With the legs paralyzed, the subjects accomplished these critical sub-tasks using a number of maneuvres by the pelvis and trunk, with the assistance of the upper extremities. The kinematic results of our study (Fig. 2) indicate that during the leg raising subtask, the trunk experienced flexion to the contralateral side, to help achieving foot clearance, and rotation to the ipsilateral side, to position the hip joint posteriorly and prepare the leg for swing as a passive pendulum in the next subtask. These kinematic maneuvres have been also reported by previous investigators.[38,39] Then during the leg swing subtask, the trunk underwent extension and contralateral side rotation in order to produce a propulsive effect for moving the leg forward. The role of the trunk maneuvres was also important in positioning the CoM in front of the knee joint of the stance leg, throughout the gait cycle, in order to keep it locked. As our EMG results (Fig. 4) suggest, the trunk's lateral maneuvres were realized mainly by the reverse actions of the scapulothoracic and shoulder girdle muscles e.g. TC, PD and LT, especially in the contralateral side, rather than ipsilateral paraspinal and abdominal muscles. This suggestion is supported by the ipsilateral activities observed for the IC, LG and EO during leg raising (Fig. 4), while the trunk was flexed laterally to the contralateral side.

On the other hand, the kinematic results of our study (Fig. 2) indicate that the pelvis maneuvres are also of great importance in providing the foot clearance and leg propulsive force. The ipsilateral activation of the QL, EO, LG and IC, observed in our study (Fig. 4), suggest that the pelvis lateral movements are contributed mainly by the reverse actions of the paraspinal and abdominal muscles, while the thoracic spine is stabilized by the scapulothoracic and shoulder girdle muscles.

The results of our study for the contribution of the TUEM into the paraplegic gait are in general agreement with the previous case reports.[17,18] Our study, however, examines a larger number of TUEM in eight SCI individuals and reveals the detailed TUEM actions during each functional subtask of the gait cycle, in association with the relevant kinematic and dynamic maneuvres, which have not been available before. These findings can help training paraplegic individuals with selective muscle strengthening programs to postpone the fatigue occurrence, as well as developing more effective mechanical gait orthoses that facilitate the generation of both the foot clearance and the leg propulsion force. However, they might be limited to the specific group of paraplegic individuals, with T12 SCI level and very high upper extremity and very low lower extremity motor scores (Table 1), that were examined in this study. Future studies should investigate the gait pattern and excitation levels of the TUEM in paraplegic individuals with other SCI levels, motor scores, and ASIA grades, in order to provide generalizable results. In particular, the locomotion pattern and the role of the TUEM in individuals with the capability of partial

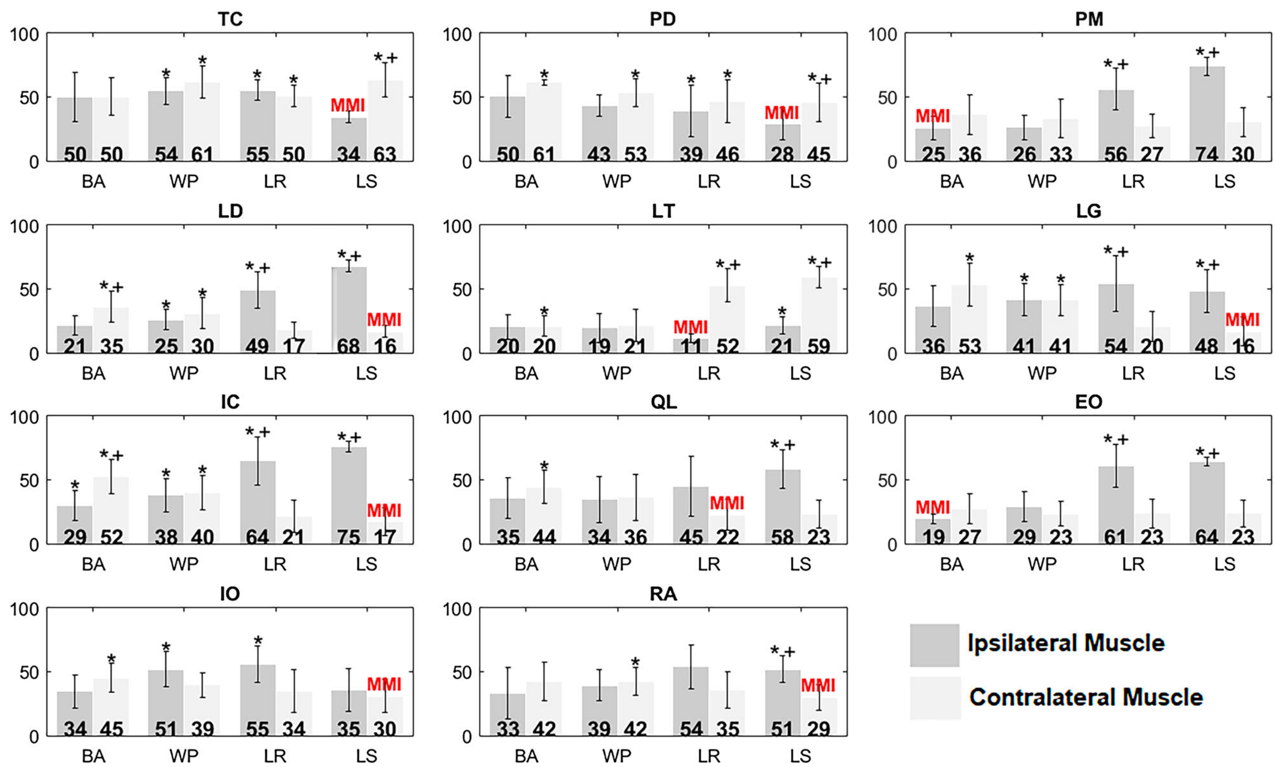


Figure 4 The mean EMG intensities of the TUEM during the eight subtasks of a complete gait cycle. The standard deviations are shown as error bars. Abbreviations: BA, balance adjustment; WP, walker propulsion; LR, leg raising; LS, leg swing. *Significantly higher intensity ($P < 0.05$) compared with the MMI. +Significantly higher intensity ($P < 0.05$) compared with the contralateral side.

volunteer contraction in lower extremities might be quite different and needs further investigation. Finally, our study acquired the EMG signal from only some of the major TUEM, due to the technical limitations. Future studies are suggested to examine the EMG intensities of other TUEM, e.g. rhomboid, serratus anterior and infraspinatus, as well as the lower extremity muscles.

Conclusion

The paraplegic walker-assisted gait can be described, based on a functional framework, using four subtasks: (1) balance adjustment, (2) walker propulsion, (3) leg raising, and (4) leg swing. The trunk and upper extremity muscles play an important role in performing these subtasks, particularly for the latter two that involve large lateral maneuvres by the trunk and pelvis.

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Disclaimer statements

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